User Manual for the Third-Generation, Advanced Piston Corer Temperature tool (APCT-3)

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Acknowledgements and Preface

This document describes tools and programs that were developed in support of international scientific drilling. Primary funds in support of this work were provided by German Science Foundation (DFG) grants Vi 133/9-1 and Vi 133/9-2 to H. Villinger (University of Bremen, Bremen, Germany) and by grants JSC 2-04 from the U. S. Science Support Program to ODP and OCE-0326699 from the U.S. National Science Foundation to A. Fisher (University of California, Santa Cruz, CA). Many individuals contributed to this development effort, including members of the engineering and operations groups at the U.S. Implementing Organization to IODP (formally ODP), particularly Kevin Grigar who designed the new APCT-3 coring components and prepared machine drawings, the tool development group at Antares (Sturh, Germany), staff from the Scripps Institution of Oceanography Hydraulics Lababoratory, and scientists and technicians of IODP Expedition 311. We are grateful to these individuals for their generous contributions of time and advice, and to the US-IO to IODP for the loan of equipment needed to develop and test the new tools.

The last generation of tools developed for measurement of temperatures while APC coring was introduced to the scientific drilling community in 1991. Much has changed in the last 16 years, including increasing demand for capabilities to quantify subseafloor thermal conditions, and remarkable improvements in computational speed and electronics stability, accuracy, and resolution. We do not imagine that this will be the last APC tool development, or that this document will comprise the "final word" on use of the third-generation tools. We encourage users to make modifications to this User Manual as needed. If changes are made to this document, please be sure that they are carefully noted, that all copies of the User Manual are updated, and that electronic materials are archived.

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I. Introduction

A. Goals and Organization

This user manual accompanies the third generation of hardware and software to be used to determine subseafloor temperatures within sediments during piston coring operations. This manual is intended to guide shipboard scientists and technicians in (1) the use of the APCT-3 tools to collect subseafloor thermal data, and (2) application of software designed to help with interpretation of these data. Although it seems like it should be a simple matter to determine the temperature of subseafloor sediments while coring, in practice it can be challenging to collect high-quality data and interpret this data correctly. We have attempted to explain and summarize sufficient information so that a novice user can collect and interpret data with the APCT-3 system, but it is important to discuss the information and recommendations in this manual with experienced scientists, technicians, and the drilling crew.

The rest of Section I contains background information on the history of temperature measurement while APC coring, which may be useful to know about in order to understand why the current system was designed and constructed the way that it is. This section also contains a few references to previous scientific and technical studies. Section II comprises an overview of APCT-3 system components and tool operation procedures. These are summarized at the end of this section with two "*Quickstart*" documents that are intended to remind experienced users what steps to follow and in what order during routine operation of the tools.

Section III focuses on data processing and interpretation, with an emphasis on a newly-developed model representing tool response during deployment. The new processing software includes a helpful graphical user interface and provides considerably greater control on parameter selection than did earlier software, and the ability to explore parameter dependences of extrapolated temperatures. Inexperienced users should pay particular attention to Section IIIA, which discusses limitations of the modeling approach and ambiguities that are likely to remain in interpretation of formation temperatures, even when the tool is deployed properly and works well.

Section IV comprises references cited throughout the manual. Appendix A1 is the latest version of the tool data sheet used by the US-IO when running the APCT-3.

Appendix A2 contains technical documents, machine drawings, and other information provided by the electronics vendor. Appendix A3 comprises a discussion of APCT-3 calibration and compilation and interpretation of calibration data collected for the first three production tool sets in Summer 2006. This information is helpful for evaluating tool accuracy and calibration limitationsm. Appendix A4 contains installation and other information on *TP-Fit*, the new APCT-3 processing program that runs through Matlab.

B. Brief history of APCT measurements and tools

Measurements of *in-situ* temperature have been made in oceanic sediments during scientific drilling since before the Deep Sea Drilling Project (DSDP) began [*Von Herzen and Maxwell*, 1964]. New tools were developed and modified during DSDP [*Horai*, 1985; *Uyeda and Horai*, 1980] and during the Ocean Drilling Program (ODP) [*Davis et al.*, 1997; *Fisher and Becker*, 1993; *Shipboard Scientific Party*, 1992a], the successor to DSDP. In some cases, temperature tools were run during drilling programs to resolve specific geothermal, hydrogeologic, or paleoceanographic questions, but in other cases, data were collected during routine operations even though they were not central to primary expedition goals (see summaries of DSDP and ODP thermal studies: [*Erikson et al.*, 1975; *Hyndman et al.*, 1987; *Pribnow et al.*, 2000]).

Temperature measurement tools in scientific ocean drilling comprise a subset of *third-party* tool developments (designed, built, and tested independent of the primary scientific operator or its subcontractors) that have contributed to both the success and the enduring legacies of these programs. One of the most innovative down hole tool developments in the latest years of DSDP was a piston coring shoe with temperature-measurement capability [*Horai*, 1985; *Horai and Von Herzen*, 1985; *Koehler and Von Herzen*, 1986]. This tool allowed DSDP (and later, ODP) personnel to determine *in-situ* temperatures within the undisturbed formation, well ahead of the drilling bit, without making a dedicated tool run. These tools have been used successfully in many geological environments to evaluate thermal conditions within sub-seafloor sediments and in open boreholes. Although the piston coring system in DSDP was initially referred to as the HPC, subsequent improvements created an advanced piston coring (APC) capability. A temperature tool run with this system is herein referred to as an "APCT tool."

Eight APCT tools based on the design introduced during DSDP were purchased by the ODP science operator [Texas A & M University (TAMU)] in 1984 and were used extensively during the early years of the new program. All of these tools were eventually lost or damaged over time, and by ODP Leg 117, it was necessary to begin building a new set of instruments. A second-generation APCT tool development was completed in 1991. This tool system was designed and built on contract by a commercial engineering company, under the supervision of ODP personnel. The new tools were placed on the *JOIDES Resolution* for use during Leg 139 and operated for over 15 years. The second-generation APCT tools differed from first-generation tools in several important ways.

The first-generation tools were based on custom-designed and -constructed electronics, bonded with epoxy into a form about the size of a small package of chewing gum (Fig. I-1A). A metal probe containing a thermistor extended from the base of the tool, and a separate battery pack was attached with a small connector. Both the tool and battery pack fit into a slots milled into the wall of a conventional APC coring shoe. These first-generation APCT tools were a marvel of technology, especially considering that they were created in the early 1980's, but they were fragile instruments (particularly the connectors) and had to be removed from the coring shoe after each deployment in order to recover data. The second-generation tools were designed around a cylindrical tool frame that fit into an annular cavity in the base of a redesigned APC coring shoe (Fig. I-1B). Two prongs extended from the base of the tool frame, one of which contained a platinum resistance-temperature device (RTD); the other prong helped to "register" the tool frame as it was lowered into the annular cavity. Batteries were contained in two separate packs that fit into the tool frame, and the tool could be programmed, deployed, and downloaded without removing the tool from the coring shoe. As of winter 2003, many of these second-generation tools had been lost or damaged, and the company that had built and serviced these tools had gone out of business.

Development of a third generation of APCT tools began in 2003, with support provided by the German Science Foundation (to H. Villinger, University of Bremen) and the U.S. National Science Foundation (to A. Fisher, University of California, Santa Cruz). The technical development was completed in close collaboration with Fa. Antares (Stuhr, Germany), who had previously collaborated with H. Villinger and colleagues on

development of a Miniaturized Temperature Logger (MTL) project, for use with collection of thermal data during conventional gravity- and piston-coring operations (Pfender and Villinger, 2002; Jannasch et al., 2003).

Hardware designs were discussed through 2003 and into 2004, and it was decided to retain as much as possible of the form and function of the second-generation tools, which had proven to be robust and easy to operate. Designs for coring components were prepared by engineers working with the U.S. Implementing Organization (US-IO) to IODP, and new coring components were built by an established vendor. Antares personnel created a series of prototype tool frames so that the fit into the coring components could be confirmed, and produced a working prototype tool in advance of IODP Expedition 311 (Cascadia Hydrates). APCT-3 project co-PIs and colleagues worked closely with Expedition 311 researchers, who calibrated and field-tested the prototype tool, which worked extremely well and generated useful thermal data [*Heesemann et al.*, 2007]. On the basis of this experience, project researchers requested several important design and functional changes to the APCT-3 electronics, and Antares personnel responded by producing redesigned tools in Spring 2006. These instruments were taken to the Hydraulics Laboratory at the Scripps Institution of Oceanography in Summer 2006 and calibrated across a working range of 0–45 °C (see Appendix A3 for a discussion of calibration procedures and examples of results from the 2006 calibration effort). This user manual was assembled in Spring and Summer 2007.

II. APCT-3 Components and Operation

A. APCT-3 Components

1. Introduction

The APCT-3 system comprises three main components: coring hardware, electronics, and operating software. The first two sets of components are discussed in this section, and operating software is discussed in the next section in the context of running an APCT-3 measurement station. Chapter III discusses processing and interpretation of APCT-3 data (and data collected with earlier generation tools) using newly-designed software.

2. Coring hardware

The US-IO drilling crew and technicians handle almost all aspects of coring operations, but APCT-3 operators benefit from understanding how APCT coring components interface with regular coring components and operations. In addition, the APCT-3 includes a new option for running multiple tools during a single APC deployment; this last capability remains to be tested.

The layout of the APCT-3 illustrates the primary coring components (Fig. II-1). APCT-3 electronics are deployed inside a coring shoe (and, optionally, an upper tool sub). The APCT-3 shoe differs from the shoe used with second-generation tools only in the depth extent of the o-ring surfaces (they are slightly longer) and in labeling instructions for the vendor. During conventional use (as with earlier-generation APCT tools) a regular APC core-catcher sub forms the seal at the top of the annular cavity. The APCT-3 tool prototype was deployed in this way during IODP Expedition 311 and the NGHP ("India Hydrate") expeditions, and it is anticipated that most future tool deployments will use this same configuration. [**NB:** the deeper o-ring surface inside the APCT-3 coring shoe should not lead to any incompatibilities with existing coring hardware, but some hardware made for the new system may not fit properly with that for the second-generation system. Be sure to fit-test any hardware as part of preparation in advance of deployment.]

As part of the APCT-3 development, an option was created to deploy two sets of APCT-3 electronics, with a sensor-to-sensor spacing of approximately 57.2 cm (22.5 in)

(Fig. II-1). If two electronics sets can be used simultaneously to determine correct *in-situ* temperatures, this will allow determination of a thermal gradient during a single coring run. Creation of this capability required design of three new components: cross-over sub, upper tool sub, and a new core-catcher sub (Fig. II-1). Prototypes of the first two of these components were created as part of the new tool development, but (as of Summer 2007) the last component will need to be constructed before the complete system can be run with two APCT-3 temperature loggers.

It is important to note that, although the annular cavities of the upper tool sub and coring shoe are identical (allowing the same electronics frames to be deployed in either location), other geometries of these components are significantly different. The coring shoe tapers near the cutting end (Fig. II-1), placing the APCT-3 thermistor probe within ~1-2 mm of the outer surface of the shoe. In addition, the taper of the cutting shoe helps to assure that it makes good thermal contact with the surrounding formation. In contrast, the upper tool housing is cylindrical in cross-section (except for wrench flats that extend across the housing 90° from the hole containing the thermistor probe), meaning that the wall between the thermistor probe and the formation is considerably thicker than in the coring shoe, ~8-9 mm. Perhaps of greater concern, the lack of a taper near the thermistor probe in the upper tool sub means that the development of a damaged zone (or "skin") outside the upper tool sub could limit the thermal contact between the tool and the formation. The numerical models developed for use with the coring shoe, as discussed in Chapter III, will have to be revised for interpretation of tool from the upper tool sub, which is expected to have a somewhat slower equilibration response.

Finally, deployment of the complete APCT-3 system, including the cross-over sub and upper tool sub, will place the butyrate core liner back about 40 cm (16 in) relative to the front of the coring shoe, compared to conventional APC operations, making the core pass through a longer section of metal before entering the liner. It is not known if friction between the core and metal components will cause greater core disturbance or limit recovery. Testing will be required to resolve this question and determine if the complete APCT-3 system can be run routinely without compromising recovered core.

3. Electronic components

The primary APCT-3 electronics are built into an aluminum, cylindrical frame (Fig. II-2). Four flat surfaces are machined onto the frame, two of which are currently used to hold electronic boards, and two of which remain empty for potential future use. One of the boards holds the measurement circuit for the thermistor probe, processor, analog-digital converter, and memory. The second board holds two 1.5-V batteries in series, providing the 3-V power supply to the tool. On the top of the cylindrical frame are threaded holes for use with the tool insertion-extraction tool, and female mini-banana plug contacts for communication with the deck box and computer. There are two o-rings on the cylindrical frame, one near the top, one near the base. On the bottom of the cylindrical frame are two prongs, one of which is empty, and the other containing the thermistor probe (nominal 30 kOhms at 25°C). A second thermistor or other sensor could be placed in the empty prong as part of a later tool modification (Fig. II-2).

The electronics are programmed using a desktop or notebook computer running Windows XP (no tests have been run using Vista; limited testing has been performed using Windows 98, but vendor specifications do not include support for this operating system). Communications is accomplished using serial communication, either through a DB-9 serial port on the computer or a USB port and a serial adapter. The communications cable attaches to a deck box, from which a second cable connects to the APCT-3 electronics. There is a special connector at the end of this cable, with male mini-banana plugs attached to a curved form, shaped to fit into the top of the annular cavity in the APC coring shoe when the electronics frame is installed (Fig. II-2). This allows the APCT-3 electronics to be programmed and deployed, and data to be recovered, without removing the electronics frame from the APC coring shoe.

A frame insertion-extraction tool is used when placing the APCT-3 electronics frame in the coring shoe or removing it for servicing. Ideally, a tool might be placed in a coring shoe near the start of an expedition, and not removed until the end of the expedition, minimizing opportunities for damaging the electronics. A top ring (machined steel with inner and outer o-rings) fits above the APCT-3 electronics frame when it is inserted in the coring shoe, protecting the tool (and particularly the electrical contacts, which are otherwise exposed on the top surface of the tool frame) from water, grease, and mud.

B. Collecting APCT-3 Data

1. Physically preparing the APCT-3 tool

(1a) If you are not familiar with operation of the APCT-3 tool, take time in port or during transit to review these instructions and run bench tests. Find an APC coring shoe with the annular cavity and place it on the lab bench on a stand that will prevent the shoe from falling over. The tools are kept in plastic cylinders that help to keep them clean and prevent the electronics or prongs from being damaged. Please keep the APCT-3 electronics either inside the plastic cylinder or in an APC coring shoe; the electronics should not be left exposed on the counter. Unscrew the top of the plastic cylinder and remove the tool. If you just want to inspect or clean the electronics, you can extract the frame from the plastic case by pushing your hand inside the frame, then lifting up. However, if you are planning to insert the frame into the APC shoe, use the insertion-extraction tool

(1b) The insertion-extraction tool has two screws topped with thumb knobs that are used to secure the tool to the electronics frame. Place the insertion-extraction tool on top of the electronics frame and turn the thumb knobs to make up the insertion-extraction tool tight to the frame. There are two sets of threaded holes in the top of the frame that are compatible with the insertion tool. As of summer 2007, one set of threaded holes is blocked (protected) with set screws, and the other set includes holes that will align the insertion-extraction tool with the electrical contacts on the top of the tool frame. When installed properly, a small vertical groove near the top of the insertion tool will align with the thermistor probe, making is easier to insert the frame in the coring shoe. Before lifting the frame using the insertion-extraction tool, back out the large wing-nut in the center of the insertion-extraction tool so that ~3 cm of threads are exposed. This will raise a central piston inside the insertion-extraction tool, allowing the electronics frame to be landed in the base of the annular cavity.

(1c) Clean the o-ring grooves and clean and grease the o-rings on the electronics frame. Use Dow 4 or similar o-ring grease.

(1d) Before the electronics frame is installed in the APC coring shoe, the thermistor probe should be coated with heat sink compound to assure a good contact with the shoe. Tools were delivered to the US-IO along with a small tub of AOS non-silicone HTC heat sink compound (part 52050-1J0), which has a thermal conductivity of 2.6 W/m-K, considerably higher than conventional heat sink compounds. Holding the frame in one hand with the handle on the insertion-extraction tool, use a small applicator (wooden stick, end of a zip-tie, etc.) with the other hand to apply a thin coating of heat sink, perhaps 1-2 mm thick, around the thermistor probe. Be sure that you apply heat sink compound only to the thermistor probe, and not to the empty prong; the thermistor probe can be identified by the wires extending from the main circuit board into the probe. Also try to keep the heat sink compound on the probe. The heat sink compound will not damage the electronics, but inevitably there is some spreading of the compound onto tool components (and fingers), and this can make the system more difficult to handle and could foul the electrical contacts.

(1e) Align the probe with the APC coring shoe – there should be a short vertical scratch or a paint mark extending from the lip of the coring shoe that indicates the location of the hole at the base of the annular cavity into which the thermistor probe will be placed. Hold the insertion-extraction tool by the handle and position the electronics frame so that it is aligned with the annular cavity. It may help to have someone else hold a flashlight or to use a camping light on your forehead during this process, so that you can see to the base of the annular cavity. As you lower the frame into the cavity in the coring shoe, watch the alignment mark near the top of the insertion-extraction tool. This should align closely with the vertical mark on the coring shoe when the frame is oriented correctly. The o-rings on the electronics frame will cause a small amount of friction as the tool is lowered into the cavity, but you should not have to push hard. If there is much resistance, extract the frame and examine the o-rings and cavity in the shoe to see if there are any obstructions. If the thermistor probe lands on the bottom of the annular cavity but misses the hole, gently raise and lower the frame until you find the hole, then lower the frame until it lands on the bottom of the cavity. [**NB:** over time, the APCT shoe or

electronics frame may deform slightly, requiring that smaller o-rings (or possibly no o-rings) be used on the frame.]

(1f) If you are preparing for an actual deployment (as opposed to running a bench test), clean and dress the o-rings in the top ring. Fill out the top of an APCT Data Sheet (Appendix A1). You will need to keep this sheet with you during the station, filling it out as events occur, to help with data interpretation after the station is complete.

2. Programming for data collection

(2a) Connect the serial cable to the computer and to the deck box, then connect the deck box to the tool cable, which ends with the curved connector. [**NB**: Shipboard technical staff should have configured the computer to be used for operating the APCT-3 electronics. Ask if you are not sure where to find the operating software, where to store data files, etc.]

(2b) Run *WinTemp*. Insert the mini-banana plugs on the curved connector into the contacts on the top of the tool electronics.

In the following *WinTemp* instructions, typed commands are listed in **bold**. In almost all cases, after entering something at the keyboard, you need to press the <enter> or <return> key (or select the *Enter* button or the *OK* button in a pop-up window). Occasionally you may need to press a special key or button; I'll identify these by placing the key name inside <triangular brackets>. Finally, you may need to select a menu or window item, listed in this manual in *italics*.

(2c) Verify that electronics are working and you have communication by choosing *Logger* → *Online* from the main menu. You will see a real-time listing of digital counts, resistance, and temperature, updated once/second. Choose *Offline* to return to the main screen. Choose *Logger* → *Battery* and record the Voltage and Total Sample Count on the Data Sheet. We don't have enough experience yet to know how long a single set of

batteries will last during normal operations; collection of this data will be helpful in evaluating tool performance over the long term.

(2d) Choose *Logger* → *Clear data* to prepare the tool to collect new data. Confirm your choice. *WinTemp* will tell you if data are already cleared.

(2e) Choose *Logger* → *Setup* to prepare for a new deployment. There is a check box listed in the Logger Time part of the Setup window that will synchronize the tool clock to the computer clock. Make sure that the computer clock is properly set before proceeding; having the tool clock set at a time different from the correct time could lead to problems later with data interpretation. Also, be sure you know if you are working in local time or GMT (UTC), and mark the data sheet accordingly. **NB:** Use of GMT (UTM) is standard in marine science observations.

Choose the intended date and time at which you would like the tool to start logging. Make sure that this time is at least several minutes ahead of the present time. Choose the duration of logging and the logging interval. Check the Calculated End Time display to make sure that the tool will run for the time intended. When the tool is configured to your satisfaction, press *Activate*. As an alternative, you can press *Start Now!* and the logger will begin logging immediately. In this case, the tool will run for the duration indicated, and will complete logging somewhat sooner than the time listed in the Calculated End Time display.

WinTemp presents a Verification window that shows selected parameters, giving the operator a chance to revise the logging plan. The time until logging will begin is shown. If *WinTemp* finds no problem, the *OK* button will be colored green. If the *OK* button is grayed out, there must be a problem with the selected program. Press *Cancel* and return to Setup if needed to revise the sampling plan.

3. Running the station

(3a) After the tool is programmed to run, remove the electrical connectors from the top of the tool. Place the top ring (with clean, dressed o-rings) above the electronics frame. [**NB:** if you insert the top ring by hand, rather than using the insertion tool, be sure that you leave the threaded holes facing up! If you do not do this, it will be difficult to get the top ring out later.]

(3b) The core tech should provide a core catcher sub. Clean and dress the o-rings, then insert the core catcher sub into the top of the coring shoe and make it up by hand so that only a few threads remain exposed, to limit opportunities for water, dirt, or grease to foul the electronics. Hand the untightened assembly to the core tech or another member of the rig crew. The rig crew will tighten the core catcher prior to deployment using the special wrench made for the APCT shoe. You will generally want to hand over the tool to the rig crew 20–40 minutes before they send the core barrel down the pipe, and they will want to be ready before the driller announces that the last core is on deck. The rig crew will make up the APCT-3 coring shoe and core catcher sub to a core barrel, then will lower the barrel into the pipe on the sand line. When the core barrel has been launched, put on your steel-toed boots, grab a hard hat, go to the driller's shack (with the Data Sheet), and let the driller know how you would like to run the station.

(3d) The core barrel is usually pumped down the pipe on the sand line until the core barrel is a few tens of meters above mudline. Let the driller know in advance if you would like to stop at mudline to record a bottom water temperature. The APCT-3 tools have been carefully calibrated (see Appendix A3), but it is good practice to verify bottom water temperature at each site at least once for each electronics set used during an expedition. More frequent bottom water measurement may be desirable, particularly when working in shallow water or in other environments where bottom water temperature variations are expected. The drill pipe is an efficient heat exchanger, so water in the pipe is generally close to bottom water temperature by the time the water reaches the bottom of the pipe, provided that the water is sufficiently deep and that the surface water is not anomalously warm. However, depending on the pumping rate and the ambient hydrography, water in the pipe may not equilibrate with bottom water if the pumps are

running quickly. In addition, the complete APCT-3 system is thermally massive, and the best bottom water temperature measurement will be made by holding the tool stationary, a few meters above mudline, for 10-15 minutes with the pumps off. When positioning the tools at mudline, be sure to take into account the length of the core barrel. If the tool is inadvertently held below mudline, a spurious bottom water temperature will be determined.

(3e) After measuring the bottom water temperature, the driller will lower the tool into the bit, pressurize the drill string, and fire the core barrel into the formation. Wait 8-10 minutes for the tool to partly equilibrate with the formation. The driller will pull the tool out and return it to the rig floor. Some researchers like to pause again at mudline during tool recovery, but the tool tends to equilibrate more slowing during this time because it is thermally more massive than during deployment (because it contains sediment). Your best bottom water temperature measurement is made prior to collection of a core.

Be sure to mark the data sheet to indicate the time of penetration and whether pressure "bled off" normally following APC deployment. Complete bleed off of pressure generally indicates a normal deployment, with the expectation that the APC coring shoe penetrates ~9.5 m ahead of the bit; actual depth will be calculated on the basis of recovery. However, if normal pressure bleed off does not occur, this generally indicates an incomplete stroke of the APC, and the driller will release the pressure manually. Once again, APC shoe penetration can be calculated on the basis of recovery.

A note about APC pull out and partial penetration:
Normally, the crew will switch over to XCB coring after an APC pull out of 60-100 klbs (this decision is left to the rig crew, Operations Superintendent/Tool Pusher, and Operations Manager). You may wish to discuss this decision in advance so that you can determine when to run the APCT-3 system. Leaving the APC barrel in the mud for the extra minutes required by APCT operation allows the formation to settle in around the tool and may increase the pull needed to remove the tool from the mud. During some APCT runs, when the sediment firmed up at shallow depths, researchers agreed to pull

out after just 6-8 minutes. If the tool is left in for any time period less than this, it may be difficult to get enough of an equilibration curve to extrapolate a meaningful temperature, but much depends on drilling conditions, water depth, sea state, lithology and other factors. You can experiment with the length of measurement with the *TP-Fit* software.

During later ODP and early IODP operations, drilling crews continued to APC to great depths (300 m or more) using a "drill-over" technique. The APC drill bit was advanced the length of recovery following incomplete stroke, and another APC barrel was launched. This approach requires more time, since the depth increment of each core might be only a few meters, but it allows collection of high-quality APC samples, and APCT-3 data, to much greater depths than have been attained previously. Discuss this option early in the expedition (or during pre-expedition planning) if deep APC (and APCT-3) penetration is important to scientific goals for your expedition.

4. Recovering the tool and data

(4a) When the tool comes back on deck the rig crew will break the shoe and core catcher sub connections. Be sure that they use the special APCT wrench to break the connection and that they unscrew the cross-over by one thread only! The core techs are well aware of the need to use the APCT wrench, but sometimes one of the less-experienced crew members will use a regular pipe wrench, and this could deform the shoe or damage the electronic components inside the shoe. After the shoe and sub have been removed from the core barrel, the IODP core techs may need to hammer the sediment out of the shoe. If the sub is loosened too much (more than one thread), they could drive mud and grease into the cavity above the retaining ring and damage the electronics.

(4b) After the core catcher portion of the core has been removed from the coring shoe, place the shoe and cross-over (they should still be connected) upside-down (with the cutting edge facing up) on the catwalk and hose off the inside and outside of the assembly. You may need to run a brush or some rags through the inside of the shoe to get all the mud off. Do this outside, where there is plenty of water and it will not matter if

you make a mess. If you let the mud dry it will be tougher to clean off later. When the shoe is clean, carry it to the lab and set it on the counter, again with the cutting edge facing up. Wipe off the shoe and sub with a dry rag. If the sub has water on it when you open the tool cavity, the water could drip down inside the cavity in the shoe and onto the electronics. When the shoe and sub are clean and dry, unscrew the coring shoe. You will need to either have someone hold the sub or put it in the vise to hold it until you get it unscrewed past the o-rings.

(4c) When the coring shoe is free, turn it over and place it on the stand on the counter. If you look down inside the shoe the top ring should be visible at the top of the annular cavity. Wipe off grease and mud from around the ring using Kimwipes, Q-tips, and rags. Use the frame insertion-extraction tool to remove the ring, then gently wipe any water drops off the top of the frame before attaching the electrical connector to recover the data. **NB:** do not remove the APCT-3 electronics from the coring shoe unless it requires servicing or inspection. If all goes well, you will be able to collect data from dozens of deployments without removing the electronics from the coring shoe.

(4d) Insert the electrical connector to allow the APCT-3 electronics to communicate with the computer. If it is not already running, start *WinTemp*. Choose *Logger* → *Read data* from the main menu. If the tool is still running, you will be asked to confirm that you would like to stop logging. You may be asked to identify a calibration file for use with your tool. Navigate to the appropriate directory (probably `C:\Program Files\Antares`) and choose the *.wtc with the file name matching your tool number. Data are downloaded and displayed in tabular form on the screen.

Choose *File* → *Save* to save the data. The file will automatically be named with the tool ID, followed by the date and time at which the tool started, and saved in *WinTemp* (.wtf) format. It is a good idea to also save the data in text format, for use with processing software. Choose *File* → *Export*. The data will be saved to an ASCII file (.dat), using the same naming convention. **NB:** *WinTemp* defaults to saving data to the primary *Antares* directory. You can save files to a different directory, but then the program may ask you to

locate a calibration file when you next recover data. It is easier to just save to the *Antares* directory, then to transfer the data to separate archive and working directories. It may be that future releases of *WinTemp* provide more flexibility in file locations.

(4e) Complete the Data Sheet, recording any anomalous events or tool behaviors. If you plan to deploy the APCT-3 tool again soon, you can leave the APC shoe tool out on the counter (in the stand!).

(4f) If this is the last station for several days (or the end of the cruise), it would be a good idea to clean up and put the tool components away for safe keeping. Use the insertion-extraction tool to remove the electronics frame from the coring shoe. Make sure that the central piston and shaft in the extraction tool is backed out about 3 cm by turning the large wing-nut counter-clockwise. Lower the insertion-extraction tool onto the top of the electronics frame and turn the thumb-knobs to engage the threaded holes in the top of the frame. Make up the screws snug, but not too tight, so that you don't strip the threads in the frame. If the insertion-extraction tool will not fit completely down on top of the frame, it is likely that you need to back out the central piston and shaft by turning the wing-nut. When the extraction tool is fully secured to the frame, turn the wing-nut clockwise. This moves the central piston downward and pushes against the inner wall of the coring shoe. Continuing to turn the wing-nut will "jack" the electronics frame up and out of the cavity. Keep turning the wing-nut until the frame becomes loose, then raise the handle on the insertion-extraction tool and gently lift the tool vertically.

(4g) Clean the surface of the electronics gently with a dry cloth. Wipe off excess grease or heat sink compound. Lower the clean electronics frame into the plastic cylindrical holder and screw on the cap. Put the cylinder in a drawer or on the shelf. Clean off the cutting shoes and sub(s). Put the interface box, cables, batteries and parts in Ziploc bags and place these in their boxes and/or on the shelf. Tell the ET, lab tech, or Lab Officer if supplies are needed.

C. APCT-3 Operation Quickstart

Deploy Tool (assumes electronics frame is in shoe, ready for deployment)

1. Turn on computer, launch *WinTemp*. Attach curved connector to top of frame.

2. Fill out top of Data Sheet.

3. Choose *Logger* → *Battery* and record the Voltage and Total Sample Count on Data Sheet.

4. Choose *Logger* → *Clear data.*

5. Choose *Logger* → *Setup*. Check box for *Synchronize Logger from PC Time*.

6. Set start time, logging duration, logging interval.

7. Press *Activate* and confirm plan, press *OK*.

8. Disconnect connector from top of frame.

9. Insert top ring. Make up core catcher sub. Hand to rig crew.

APCT-3 Operation Quickstart

Recover Tool (assumes coring shoe is clean, open, electronics frame is accessible)

1. Turn on computer, launch *WinTemp*. Attach curved connector to top of frame.

2. Enter time on Data Sheet.

3. Choose *Logger* → *Read Data.* Confirm you wish to stop logging, if necessary.

4. Choose *File* → *Save* to save the data in binary (*WinTemp*) format.

5. Choose *File* → *Export* to save the data in ASCII format.

6. Copy and/or backup data to archive and working directories.

III. APCT-3 Data Processing

A. Modeling and other considerations

Processing APCT-3 temperature data to determine *in-situ* conditions cannot be done automatically, but requires careful and somewhat subjective fitting of measured temperatures to theoretical decay curves. Some general understanding of the physics involved is required to make good interpretations. The description of processing steps in the following section assumes that the reader understands the general theory behind APCT measurement processing, as described by Horai and Von Herzen [1985] and Horai [1985], and Heeseman et al. [2007]. Additional insight is provided by papers describing processing of subseafloor probe data using tools with differing geometries [e.g., *Bullard*, 1954; *Davis et al.*, 1997; *Hartmann and Villinger*, 2002; *Langseth*, 1965; *Villinger and Davis*, 1987].

Discussing the procedure requires a brief review of tool responses during typical deployments (Fig. III-1). Measured temperatures drop as the APCT-3 is deployed from the ship and lowered to the seafloor. The lowest measured temperature may be found close to the seafloor, but as described earlier, this temperature may not be consistent with that of bottom water unless the tool is held stationary just above mud-line for 10-15 minutes with the pumps off. The tool is lowered to the bit, pressure is accumulated in the drillstring, and the core barrel is fired into the mud. There is an abrupt temperature rise associated with frictional heating of the coring shoe, and (for most stations) the tool temperature begins to decay towards the true *in-situ* temperature (Fig. III-1A). For stations in unusually warm sediments, the tool temperature may continue to rise after penetration (Fig. III-1C). It is not possible to leave the tool in the seafloor long enough to achieve complete equilibration. This would require 40-60 minutes or more, risking loss of the tool (and the APC core barrel) with settling of sediment around the core barrel. Instead, partial equilibration is achieved, and the core barrel is recovered by wireline.

Processing of APCT-3 data to infer the *in-situ* formation temperature requires extrapolation of a short record of thermal equilibration. The programs used for this purpose with the first- and second-generation APCT tools were based on the assumption that tool response was consistent with a one-dimensional, radial geometry [*Horai*, 1985]. Fitting data to a model based on this geometry is based on the assumption (proven to be

largely appropriate) that radial heat transfer away from the tool is much more important than vertical heat transport along the tool, and that the temperature probe is sufficiently far from the end of the coring shoe that there is little influence associated with the contrast in properties between the shoe and deeper sediment. As part of the development of the APCT-3 system, new cooling curves were calculated numerically on the basis of the geometry of the coring shoe and core barrel. In addition, earlier programs were based on a fixed, analytical relationship between sediment thermal conductivity (k) and heat capacity (ρc). New cooling curves have been calculated using a wide range of k and ρc values, allowing the user to select values that seem most appropriate, and to explore the influence of parameter selection interactively.

The general procedure is to select formation properties, select an interval of data to be processed, and shift the tool penetration time so as to minimize the statistical misfit between the measurements and the model. Once an appropriate fit is achieved, temperatures are extrapolated to infinite time, using the model, to infer the *in-situ* formation temperature. Users typically neglect the first 30-60 seconds of data following penetration, as these measurements often deviate from theory for several reasons, including the non-instantaneous and variable rate of tool penetration, and the non-uniform distribution of frictional heat. The data interval selected for processing is usually no longer than 7-9 minutes, sometimes less, in part because of limited time with the tool motionless in the seafloor, but also because deviations of tool cooling from the theoretical model tend to occur at later times.

Selection of formation properties is challenging for several reasons. First, sediment thermal conductivity is heterogeneous in many formations. Second, DSDP, ODP, and IODP scientists typically do not determine sediment heat capacity, and there is no single relation between thermal conductivity and heat capacity that applies for all sediments. Third, thermal conductivity measurements are virtually never made at exactly the same location as the temperature probe, and even if they are, recovered sediments from the coring shoe are often highly disturbed. Thus researchers must be prepared to process data using a variety of reasonable properties, and to list *in-situ* temperatures determined through processing with uncertainties that span a range of values.

The time shift applied during processing to optimize the statistical fit between observations and model calculations has a long history in analysis of seafloor heat flow data [e.g., *Bullard*, 1954; *Davis et al*., 1997; *Hartmann and Villinger*, 2002; *Langseth*, 1965; *Villinger and Davis*, 1987]. The time shift is a heuristic representation of several properties and processes that are virtually impossible to predict *a priori*: finite tool insertion time, irregular heating, creation of a damaged zone around the coring shoe (inside and/or outside) having different sediment properties, fluid movement away from the tool for a brief period after penetration. Experience has shown that it is often difficult to achieve a good fit between observations and modeled temperature decay without allowing for the time shift. However, this additional degree of freedom in data processing can also accommodate use of a theoretical model that is inconsistent with actual tool and formation geometry or properties. We do not have much experience yet with the new APCT-3 cooling curves, and there remains to be completed a detailed comparison of older and newer decay curves and their influence on inferred *in-situ* temperature, but it appears that time shifts required to "best-fit" the data using the new model may be somewhat shorter than those needed with the older models. This suggests that the newer models may do a better job representing experimental conditions.

It is also important in selecting a data interval during processing to examine the experimental data very carefully, and to avoid data segments that show evidence of tool motion. In some cases, the tool is moved abruptly and this results in a second heating pulse that is clearly visible, but in other cases, there can be a subtle change in the rate of cooling. If data are used in processing that include secondary heating because of tool motion, a spurious formation temperature may be inferred. This issue illustrates one of the great challenges in processing APCT data in general: a high-quality statistical fit does not assure that the extrapolated formation temperature is correct. Experience has shown that, in many cases, extrapolated temperatures from what appear to be excellent records are inconsistent with *in-situ* temperatures determined at higher and lower depths (i.e., an extrapolated value falls of an otherwise consistent thermal gradient). Sometimes the conundrum can be resolved by reexamining the questionable data record, but in other cases, the reason for the inconsistent extrapolated temperature remains enigmatic.

B. TP-Fit

TP-Fit is a Matlab program created for processing of APCT-3 data. Because the geometry of the new tool is essentially identical to that of the second-generation tool, *TP-Fit* will also work with older data, provided they are properly formatted. Installation and general Matlab and program operation are discussed in Appendix A4. In this section, it is assumed that Matlab and *TP-Fit* are properly installed on the computer to be used, and that the user has access to one or more APCT-3 data sets. Example data sets are provided with the *TP-Fit* software.

As with the earlier discussion of *WinTemp,* instructions for *TP-Fit* follow some general conventions. Typed commands are listed in **bold**. In almost all cases, after entering something at the keyboard, you need to press the <enter> or <return> key (or select the *Enter* button or the *OK* button in a pop-up window). Occasionally you may need to press a special key or button; I'll identify these by placing the key name inside <triangular brackets>. Finally, you may need to select a menu or window item, listed in this manual in *italics*. [**NB:** most *TP-Fit* functions can be run without the graphical user interface, from the Matlab command line, but all instructions herein assume that the user is running TP-Fit using the Graphical User Interface. See Appendix A4 for more information.]

(1) Start Matlab, then **cd** to the working directory. This directory should contain the main *TPFit.m* script and folders (subdirectories) called *RefModels* and *TP-Fit*. In general, it will be best to have a single working directory for an expedition, and to bring data files into this directory for processing, then move results files out of the directory when work is complete. Be sure to follow Matlab conventions with regard to naming directories and files (avoid spaces, unusual characters, etc.).

(2) Run *TPFit* from the Matlab command line. You are presented with a vertical button window showing the typical work-flow for processing APCT-3 data. In general, buttons will be used from top to bottom. Select *Load Data* to load a data file and begin processing. When you have successfully opened an APCT data file, the *Load Data* and *Edit Meta-Data* buttons will turn green.

(3) Choose *Edit Meta-Data* and enter appropriate values. Initial values are already entered on the basis of the data file and the last values that were saved when the program was used. In addition, values for k and ρc may have been set by default. Part of data processing is evaluating the uncertainty in final temperatures caused by uncertainty in k and ρc values, but it is best to enter something that you think to be reasonable. In the last generation of APCT processing software, the user was asked to enter only a value for k, and thermal diffusivity ($\kappa = k/\rho c$) was calculated from the empirical relation of Von Herzen and Maxwell [1959]:

$$\kappa = \frac{3.657 \times (k - 0.70)}{10^{-7}}$$

where k is in W/m-k and κ is in m^2/s. Other studies have explored relations between k and κ, and the user is advised to choose a favored relation initially, but to explore the significance of this relation as part of APCT processing, as described below. Choose *OK* to close the *Edit Meta-Data* window.

(4) Choose *Pick* to select the data segment to process, and a plot window will open showing the complete data record. Three values must be selected: tool penetration time (labeled *t0*), the initial data point to fit to the model (*Data Start*), and the final data point to fit to the model (*Data Stop*). Because the data are shown in a standard Matlab plotting window, you can zoom in and out, adjust axes, etc. Most of the data are colored blue, but a subset is colored green; the latter indicates the segment of data to be processed. Zoom in on the window of data that starts before penetration and ends after penetration, including several minutes of data prior to tool penetration.

Press the *Pick* button adjacent to the *t0* box, then move the cursor to the point you would like to select to represent the time of tool penetration, and *left-click* with the mouse. Because *TP-Fit* will shift the time between penetration and the data window as part of processing, selection of exactly the right penetration time is not essential. *TP-Fit* assumes a data window to process of 9 minutes, from **60** seconds after penetration to **600** seconds after penetration. You can adjust one or both of these times by choosing the appropriate

Pick button, and using the cursor and mouse to select preferred times. When you have selected all three times, press *Done*.

(5) Press *Show Fit* on the vertical button window. You are presented with a plot window labeled *Results* containing four windows. The top window shows the penetration record, with the data points used for processing colored green and red. Points not used in processing are colored blue. Points colored red comprise the final third of the selected data window. Also shown in the top *Results* window are two estimates of the equilibrium formation temperature, labeled with green and red dashed lines. The green line is based on the full data window, whereas the red line is based on the final third of the data window. This plot also shows a thick gray line that falls behind the data points. This line shows the model curve to which the observational data are compared.

The second *Results* window shows deviation from the model by the observations. The deviations are plotted on a log-scale, as absolute values, with overestimates and underestimates shown with open and filled symbols, respectively.

The bottom two plots show how the equilibrium formation temperature was estimated. The left-bottom plot shows a cross-plot of measured and modeled temperatures. Early data appear on the upper right corner of this plot, and later data appear towards the lower left corner. Extrapolation of the (hopefully linear) trend shown in this plot back to the x=0 value indicates the interpreted formation temperature at equilibrium (what the tool would have recorded eventually, if it were left in place for a sufficiently long time). Once again, two values are indicated, one in green using the full data window, and one in red using the last third of the data window. The right-bottom plot shows the standard deviation of the misfit between the model and observations (the green straight line shown in the left-bottom plot) as a function of the time shift added to or subtracted from the penetration time.

(6) If you would like to adjust specific k or ρc values, the fastest way to do this is to return to *Edit Meta-data*, change one or both values, rerun *Pick* (you can just choose

Done immediately without changing the pick, but you must enter the *Pick* window), and choose *Show Fit*. *TP-Fit* will update the results window (and plots) with your new values.

(7) If you are satisfied with the processing at this stage and would like to save your work, use the *Save Session* button to put the workspace into a Matlab *mat* file that can be reloaded later. You can also send results of the fit analysis to a text file for plotting with different software by pressing *Make Report*.

(8) Two additional buttons are used to process APCT data using a variety of k and ρc values. Press *Compute Contours* and the program will cycle through all available models, using a range of k and ρc values, and calculate best-fitting, equilibrium temperatures for each model. As of summer 2007, models are available for $0.5 \leq k \leq 2.5$ W/m-k, and $2.3 \times 10^6 \leq \rho c \leq 4.3 \times 10^6$ J/m^3-K, in increments of 0.1. This range of values should accommodate the needs of most APCT-3 tool users. When the calculations are complete, press the *Explore* button to see the results of the analysis. You are presented with four contour plots in a new plot window labeled, *Contours*.

The top plot shows the smallest standard deviations achieved by least-squares best-fitting of each combination of k and ρc values. For high-quality data (rapid tool penetration, no motion during 8–10 minute penetration), the smallest standard deviation may be 0.01°C or less. This is the standard deviation of a particular fit of data to a function, *not* an uncertainty in the equilibrium temperature. To decide what may be an appropriate uncertainty, look at the next plot. This one shows the equilibrium temperature as a function of k and ρc. For high-quality data, there may be a range of ±0.1–0.2 °C or more in equilibrium temperatures based on selection of reasonable values of k and ρc. This is a more reasonable estimate of uncertainty in the final value (assuming high-quality data and a good fit of observations to the model).

The third plot shows how the best-fitting time shift in penetration time varies with k and ρc values, and the fourth plot shows the difference between final temperatures calculated

on the basis of the entire data window, and those based on using only the final 1/3 of the data window.

On all contour windows, the star shows the k and ρc values that minimize the standard deviation of the misfit between model and observations, and the white dot shows the currently-selected value. If you look back at the *Results* window, you will see that it has been updated to show values of k and ρc consistent with the position of the red star. You can select different values of k and ρc by moving the cursor over the top plot on the *Contours* window and *left-clicking* with the mouse. The white dot will move and, once again, the *Results* plot is automatically updated.

(9) A few comments on selecting an equilibrium temperature. None of the information shown on the contour plots can be used, by itself, to determine the "true" *in-situ* temperature of the formation. In many cases, the properties that provide the best-fit of the model to data may be unrealistic, for example, sometimes including very high values of k and ρc. The difficulty in selecting an appropriate model (and equilibrium temperature) is that, although the new models are better than the old models in replicating the tool geometry, there are aspects of each deployment that remain poorly constrained, including: the distribution of frictional heating, heterogeneities in the formation, the quality of the thermal contact between the shoe and sensor probe, the creation of a damaged zone around the shoe. Because these (and likely other) characteristics of each deployment are not well characterized, available parameters (k, ρc, and the time shift) may end up being "adjusted" to accommodate the data and improve the fit statistics. In summary, a good fit of the data to the model does not demonstrate that the model (or the equilibrium temperature) is correct. Similarly, the model that provides the statistical best fit to the data is not necessarily most likely to be correct. Ultimately, researchers will need to use all available data, particularly physical properties measurements from around the APCT measurement depth, and empirical relations between k and ρc, and consider whether an inferred equilibrium value makes sense on the context of other measurements.

C. APCT-3 Processing Quickstart

1. Put APCT-3 data in a working directory with the *TPFit.m* code (and subdirectories) and start Matlab. Run *TPFit.*

2. Select *Load Data* to load a data file.

3. Select *Edit Meta-Data* and enter appropriate values. Be sure to enter values of k and ρc most consistent with initial expectations.

4. Select *Pick* and choose the tool penetration time (*t0*), the initial data point to fit to the model (*Data Start*), and the final data point to fit to the model (*Data Stop*).

5. Select *Show Fit* and examine the *Results* plot window. Return to *Edit Meta-Data* and *Pick* as needed to examine different properties and data intervals.

6. Select *Compute Contours* and the program will complete the same calculations using all available values of k and ρc. When this is complete, select *Explore* to evaluate the influence of sediment physical properties in fit statistics, equilibrium temperatures, and other parameters.

7. Select *Save Session* to create a Matlab *mat* file, or *Make Report* to generate text output for later plotting.

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Appendices

A1. APCT-3 data sheet

A2. Tool technical information

Documents in this section comprise an assortment of drawings, instructions, packing slips, and other information related to APCT-3 tool components.

A3. Calibration

1. Goals and procedures, limitations

APCT-3 tool calibration is an important part of tool production and maintenance, but there are some common misunderstandings as to the need for calibration, how it is done, and its limitations. This section discusses these issues, and the next section reports on results of the laboratory calibration of the first three "production" APCT-3 tools during Summer 2006. A prototype tool was calibrated by A. Trehu and colleagues at OSU prior to the expedition, as described in Heesemann et al. [2007].

The determination of conductive seafloor heat flow requires measurements of the thermal gradient and thermal conductivity. What matters most from the perspective of APCT-3 measurements used to determine the heat flux is the *difference* between adjacent measurements, rather than their absolute values. However, applications involving assessment of changes in seafloor temperature do require acquisition of absolutely accurate data. In addition, use of multiple tools requires that data from these tools be directly comparable; although comparison of bottom water readings provides a loose intercalibration between tools, differences in operational procedures can make direct comparison of apparent bottom water temperatures difficult.

As described earlier in this manual, there will always be uncertainty in estimated *in-situ* temperatures determined with the APCT tool because many processes and properties are not determined. Even when very high-quality data is collected, ambiguities in processing generally result in uncertainties in equilibrium temperatures on the order of 0.1–0.2 °C. Thus the goal of calibration should be to determine the temperature recorded with the tool at any time with an absolute accuracy at least as good as 0.01–0.02°C, and perhaps as good as 0.002–0.004 °C. There are limited benefits to be gained from achieving greater accuracy in calibration with this tool system.

Absoluate calibration of APCT-3 tools requires two additional instrument systems: a stable calibration bath capable of achieving the desired temperature range, and a precision temperature reference that has itself been calibrated to the desired accuracy (e.g., with a NIST-traceable certificate of accuracy). Most calibration baths operate with simultaneous water chillers and heaters that work against each other to hold the temperature within a narrow operating range. The APCT-3 tool system is physically large

and thermally massive, so it is best to use a large, stirred calibration bath (like those used for calibration of CTD systems). In principle it might be possible to calibrate an APCT-3 tool in a smaller bath, with the coring shoe oriented vertically and the top of the shoe extending above the water level, but in practice it will be difficult to maintain constant bath temperature with this configuration.

It is not possible to calibrate APCT-3 tools under conditions identical to those of standard operation. When the tool is deployed at sea, it begins at room temperature, then cools towards bottom water temperature as the tool is pumped down the drill pipe; the tool may reach bottom water temperature if it is held steady at in bottom water, with the pumps off, for a sufficient time. When the tool is lowered to the bit and fired into the formation, the electronics changes temperature as a result of frictional heating of the coring shoe, but at a rate that is probably much lower than that of the temperature probe itself (because the tool electronics are not in good thermal contact with the wall of the coring shoe). It is during this time, when the tool electronics are drifting in temperature, that the most important data are collected for 8–10 minutes (with the tool held stationary in the sediment). How much the temperature of the tool electronics varies, and how uniform this drift is across the electronics, cannot be determined. Also, there may be significant differences in electronics temperature from run to run.

Electronic components are much more stable now than they were in the past. Functionality that used to require multi-layer circuit board (or even two boards) is now found within a single IC chip. Certainly this has helped to improve electronic stability in the presence of changing temperatures. But there may still be some thermal drift with modern electronics, and there are other (largely-unknown) factors that may contribute to variations in electronic performance. The point is not to bring into question the entire basis for APCT-3 measurements, but rather to note that the conditions of tool calibration are inevitably somewhat different from those of standard tool operation. This is another reason why it is probably not worthwhile to attempt to calibrate the APCT-3 tools to an absolute accuracy better than 0.002–0.004 °C, although the resolution of the instrument should make higher accuracy possible. Even absolute accuracy of 0.01–0.02 °C should be acceptable for the vast majority of applications, given the much larger uncertainties associated with data processing.

2. Summer 2006 calibration

The first three sets of production APCT-3 electronics were calibrated at the Hydraulics Laboratory at the Scripps Institution of Oceanography (SIO) in Summer 2006. Tools calibrated during this time have serial numbers 1858002C, 1858004C, and 1858005C. A prototype APCT-3 tool was calibrated by A. Trehu and colleagues at Oregon State University in Summer 2005 prior to deployment on IODP Expedition 311, as described elsewhere [*Heesemann et al.*, 2007].

The calibration tank used at SIO was custom built, with internal dimensions of 50 cm (width), 172 cm (length) and 36 cm (depth). This tank was large enough to allow all three production tools to be submerged simultaneously. Two of the tools were calibrated inside APCT coring shoes (one new shoe and one older shoe on loan from the US-IO) and the third was calibrated inside a new upper sub.

Tank temperatures were controlled using competing water heating and chilling systems, and spinners at each end of the tank kept the water well mixed during calibration. Tank temperatures were monitored with a Hart Scientific Model AS125 temperature probe and a Model 1521 Digital Readout. This measurement system, which had been purchased in 2002, was sent to the manufacturer for recalibration immediately before the SIO calibration, and was adjusted and certified to be accurate within an operating range of -10–50°C with accuracy of 0.001–0.002 °C (relative to an NIST-certified reference).

Collection of APCT-3 calibration data required two days at SIO. Calibration began on the morning of 16 August 2006 by inserting the three APCT-3 electronics sets in coring shoes and an upper sub, and starting each of the tools with a logging interval of 10 seconds. The shoes and subs were sealed with an end cap (constructed for this purpose) or a cross-over sub, and were bound together with straps and lowered to rest on a wooden frame on the bottom of the calibration tank. The frame held the tools a few centimeters off bottom, to allow tank water to circulate completely around the tools.

The tank was filled with water and ice and the chiller and heater were activated. About two hours were required to find the right combination of system settings to hold

the bath temperature constant near 0°C. Reference data were logged from the digital probe readout by terminal emulation with a frequency of 5 seconds.

For calibration purposes, each "fixed" bath temperature was held as steady as possible for 20–30 minutes, allowing the tools to come to thermal equilibrium with the bath. Rheostats on the bath temperature control panel were adjusted to strengthen or weaken the sensitivity of the heater and chiller switches in an effort to optimize stability. If the sensitivity was set incorrectly, the bath temperature would oscillate excessively or would drift away from the desired temperature. When we wished to change the bath temperature (always increasing from the previous stable temperature), we turned off the chiller and turned on the heater and watched as the bath temperature rose, then reset the controllers to maintain temperature when a change of about 5°C had been achieved. We made no attempt to obtain specific temperatures in the tank (e.g., exactly 15.000 °C, 20.000 °C, etc.); instead we chose temperature increments of about 5°C across a working range of 0 to 45 °C (Tables A3-1 to A3-3).

After the first calibration point, it generally took 30–60 minutes to change to a new temperature, and we held each temperature for 20–30 minutes. In fact, the bath could not maintain a completely stable temperature, but tended to oscillate about the target temperature with an amplitude of 0.005–0.010 °C and a period of 2–3 minutes. Temperatures recorded with the ACPT-3 tools also oscillated, but with a slightly reduced amplitude. Collection of 20–30 minutes of data for each calibration point allowed the tank and tool oscillations to be averaged out (Fig. A3-1).

Calibration over a range of 0–30 °C was completed during the first day, and additional calibration points at 35–45°C were completed on the second day. The tools were recovered and data downloaded and reviewed briefly before draining the bath and ending the calibration session, to make sure that the instrumentation worked as expected.

Data were processed to determine calibration coefficients. First, the reference temperature records were reviewed to determine the timing of stable temperature intervals, one for each calibration point. Next, data recovered from the APCT-3 tools were plotted to determine tool readings during the time periods corresponding to the times when the temperature reference was stable. Curiously, the three APCT-3 tools did not show the same equilibration response. Tool 1858002C tended to overshoot the target

temperature and generally took longer to equilibrate (Fig. A3-1). The first characteristic is consistent with Tool 1858002C being closer to a heater unit, whereas the second characteristic may indicate that the sensor in this tool was not in as good thermal contact with the wall of the coring shoe/sub as were the other tools.

We generally selected data intervals to process during which the reference probe and all of the APCT-3 tools were in rough "equilibrium" with the bath temperature; measured tool responses oscillated, but there was no measurable drift. The latter was assessed by selecting a 15-20 minute interval and fitting the data to a straight line. Intervals were selected so as to minimize the slope of this line. It is not possible to determine prior to recovering the APCT-3 tools when they have achieved thermal equilibrium with the bath, nor was it a simple matter to assess this with the reference probe. Data from the latter were logged using terminal emulation, so data could not be accessed until after the logging function was stopped, and there was no capability to plot the data in real time without generating data gaps. Nevertheless, by waiting 20-30 minutes after temperatures appeared to stabilize, we were able to assure that sufficiently-stable data were acquired.

The APCT-3 tools were delivered from the contractor with calibration coefficients provided by the thermistor vendor. These coefficients relate the resistance of the thermistor circuit to the measured temperature using the Steinhart-Hart equation:

$$\frac{1}{T} = A + B(\ln R) + C(\ln R)^3 \qquad \text{(A3-1)}$$

where T is temperature in Kelvin, and R is resistance in ohms. Comparison of mean reference temperatures during each stability period and apparent temperatures indicated by the APCT-3 tools (based on factory calibration coefficients) revealed absolute differences as great as 0.034 °C (Tables A3-1 to A3-3, Fig. A3-2). Errors were systematically biased and tended to be largest for higher calibration temperatures, but the offsets were inconsistent between tools.

We calculated new calibration coefficients for the three tools by fitting measured values of T and R with equation (Tables A3-1 to A3-3) to derive new coefficients A, B, and C (Table A3-4, Fig. A3-2). Comparison of temperatures calculated with new coefficients to those determined with the reference probe indicates errors ≤0.002°C for all tools across the full range of calibration temperatures; for most tools and temperatures,

the errors are ≤0.001°C. Equally important, residual errors following fit of new coefficients are distributed randomly about zero, with no systematic bias. Curiously, for all three tools, the temperature at which there is the greatest residual error in the new calibration is 35°C. This suggests that the reference reading may be in error (or may have been averaged incorrectly), but the data were checked carefully and there seems to be little difference between the reference record for this temperature and those at other temperatures. The residual errors at this temperature, while larger than those at other temperatures, are still ≤0.002 °, well within the acceptable range.

We had originally intended to explore calibration options for use with the new ACPT-3 tools, including converting directly from digital counts to temperature, or cross-plotting apparent and true temperatures, but the basic calibration attempted initially worked out so well, that there was no need for additional analyses. The new calibration coefficients determined during 2006 tests have been entered into updated calibration files (*.wtc) for the three new tools. Copies of these files are provided to the US-IO with this manual, along with back-up copies of the original factory calibrations.

A note on updating calibration coefficients using *WinTemp*

WinTemp uses unique calibration coefficients associated with each tool, stored in **.wtc* files. For example, the coefficients for tool 1858002C are stored in a file called: *1858002C.wtc*. When data are retrieved from an APCT-3 tool, *WinTemp* looks in the current (working) directory for the appropriate file for the tool being used, and requests that the user identify the file if it can not be found. When data are retrieved from a tool, they are stored in a binary **.wtf* file. This file contains a set of temperatures used to create the calibration coefficients applied by *WinTemp* to convert from resistance to temperature. Thus calibration data are embedded within each **.wtf* file. When a user wishes to export ASCII data, the header of the *.dat file contains a list of calibration coefficients used to generate the file, but not the original calibration data that are embedded within the **.wtf* file.

In order to change calibration coefficients, one must open a **.wtf* file, as this allows access to a set of calibration data. Once a **.wtf* file is open, choose *Calibration* → *Temperature* from the main menu. You are shown a set of three resistance-temperature

(R-T) pairs, and are allowed to change these values. Apparently, *WinTemp* always uses three temperatures to determine the values of the three calibration coefficients, *A*, *B* and *C*. Follow these steps to get *WinTemp* to use coefficients determined with a greater number of R-T pairs.

Determine coefficients based on calibration using more than three R-T pairs with a least-squares approach (with Excel, Kaleidagraph, Matlab, or a similar program). Use a spreadsheet to calculate three *new* R-T pairs using the coefficients just determined, spanning the full range of calibration. For example, during Summer 2006 calibration, we use a range of 0–45°C; thus we calculated three R-T pairs for T = 0, 20, 45 °C. *Make sure to cover the full calibration range, and to include values at the extreme ends and in the middle of the range.* Enter these R-T pairs in the *Calibration Temperature* window and press *OK*. The temperature values in the open **.wtf* will be updated accordingly. If you wish to save the new calibration coefficients, choose *Calibrtion → Store* from the main menu, and name the **.wtc* file accordingly. **NB:** Antares releases **.wtc* files as "read-only" so you will need to change this to overwrite an existing **.wtc* file. Be sure to back up the old file first!

The method above was used for saving new coefficients based on Summer 2006 calibration of the first three APCT-3 tools. Small errors were introduced in the specification of calibration coefficients *A*, *B*, and *C* (which are slightly different as stored in the **.wtc* files by *WinTemp*), but additional spreadsheet calculations show that these additional errors result in calibrated temperatures that are <0.001°C different from those determined using the full, 10-point calibration. **NB:** this does not mean that a 3-point calibration is as good as a 10-point calibration! Rather, the method above "tricks" *WinTemp* into using coefficients determined with a 10-point calibration, as if they were detemined with a 3-point calibration.

Table A3-1. Summary of Summer 2006 calibration results: tool 1858002C.

T_{ref} (°C)	R_{002C} (ohms)	$T_{002C\text{-}orig}$ (°C)	$T_{ref} - T_{002C\text{-}orig}$ (°C)	$T_{002C\text{-}new}$ (°C)	$T_{ref} - T_{002C\text{-}new}$ (°C)
0.1992	94104	0.188	0.0112	0.1993	0.0001
4.9558	74614	4.954	0.0018	4.9561	0.0003
10.0300	58654	10.035	-0.0050	10.0296	-0.0004
14.9440	46760	14.955	-0.0110	14.9437	-0.0003
19.9130	37416	19.930	-0.0170	19.9128	-0.0002
24.9210	30070	24.941	-0.0200	24.9209	-0.0001
30.0050	24232	30.027	-0.0220	30.0048	-0.0002
35.0350	19684	35.059	-0.0240	35.0363	0.0013
40.1180	16046	40.140	-0.0220	40.1179	-0.0001
45.1260	13189	45.146	-0.0200	45.1255	-0.0005

Table A3-2. Summary of Summer 2006 calibration results: tool 1858004C.

T_{ref} (°C)	R_{004C} (ohms)	$T_{004C\text{-}orig}$ (°C)	$T_{ref} - T_{004C\text{-}orig}$ (°C)	$T_{004C\text{-}new}$ (°C)	$T_{ref} - T_{004C\text{-}new}$ (°C)
0.1992	94211	0.165	0.034	0.1990	-0.0002
4.9558	74692	4.932	0.024	4.9564	0.0006
10.0300	58711	10.014	0.016	10.0298	-0.0002
14.9440	46801	14.936	0.008	14.9439	-0.0001
19.9130	37445	19.913	0.000	19.9130	0.0000
24.9210	30090	24.926	-0.005	24.9208	-0.0002
30.0050	24245	30.015	-0.010	30.0047	-0.0003
35.0350	19692	35.050	-0.015	35.0359	0.0009
40.1180	16050	40.134	-0.016	40.1177	-0.0003
45.1260	13190	45.144	-0.018	45.1259	-0.0001

Table A3-3. Summary of Summer 2006 calibration results: tool 1858005C.

T_{ref} (°C)	R_{005C} (ohms)	$T_{005C\text{-}orig}$ (°C)	$T_{ref} - T_{005C\text{-}orig}$ (°C)	$T_{005C\text{-}new}$ (°C)	$T_{ref} - T_{005C\text{-}new}$ (°C)
0.1992	93978	0.215	-0.0158	0.1997	0.0005
4.9558	74535	4.975	-0.0192	4.9561	0.0003
10.0300	58607	10.052	-0.0220	10.0294	-0.0006
14.9440	46733	14.969	-0.0250	14.9433	-0.0007
19.9130	37401	19.939	-0.0260	19.9128	-0.0002
24.9210	30063	24.946	-0.0250	24.9210	0.0000
30.0050	24230	30.029	-0.0240	30.0051	0.0001
35.0350	19685	35.058	-0.0230	35.0367	0.0017
40.1180	16049	40.136	-0.0180	40.1179	-0.0001
45.1260	13193	45.139	-0.0130	45.1252	-0.0008

Table A3-4. Calibration coefficients for APCT-3 tools, based on fit to Steinhart-Hart equation, $\frac{1}{T} = A + B(\ln R) + C(\ln R)^3$.

Tool ID	*A*	*B*	*C*
1858002C	9.2779185×10^{-4}	2.2234513×10^{-4}	1.2263852×10^{-7}
1858004C	9.3166619×10^{-4}	2.2183365×10^{-4}	1.2375744×10^{-7}
1858005C	9.2931769×10^{-4}	2.2203068×10^{-4}	1.2425852×10^{-7}

Notes: T is calculated in Kelvin, ω in ohms. Also, read section on entering coefficients for use by WinTemp; actual coefficients used are slightly different than those listed above, for reasons explained at the end of Appendix A3.

Figure Captions

Figure I-1. Photos of first- and second-generation APCT tools and components. A. First-generation tool developed for use during DSDP (and used in the first several years of ODP) [*Horai*, 1985; *Horai and Von Herzen*, 1985; *Koehler and Von Herzen*, 1986]. B. Second-generation tool developed by Adara Systems in collaboration with ODP staff, first deployed during ODP Leg 139 [*Shipboard Scientific Party*, 1992a].

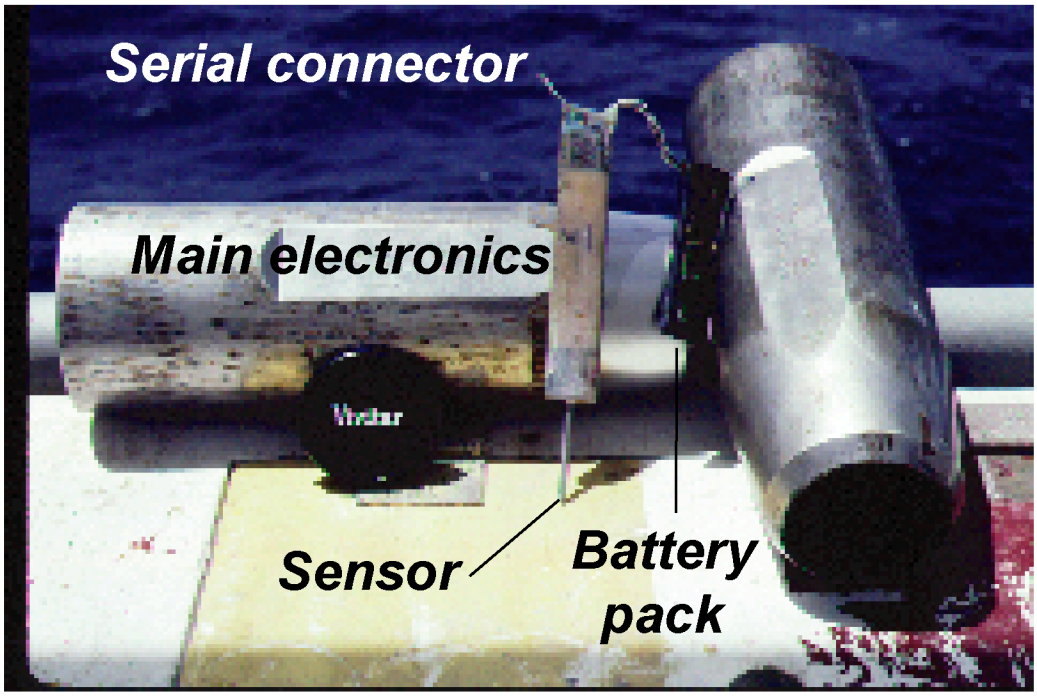
Figure II-1. Machine drawing of complete APCT-3 measurement system, including optional configuration with two electronics sets. The primary APCT-3 coring components comprise these pieces: coring shoe with annular cavity (drawing OP4375), cross-over sub (drawing OM0701), upper tool housing (drawing OM0702), and a core-catcher sub (drawing OM0703). Other components include o-rings and core-catcher components, and test plugs for sealing the coring shoe and upper tool housing during lab testing and calibration. Conventional use of the APCT-3 involves deployment of only a single electronics set, in the coring shoe. See text for discussion of parts and deployment options, and Appendix A2 for detailed drawings of tool components.

Figure II-2. Photo of APCT-3 electronics and related components.

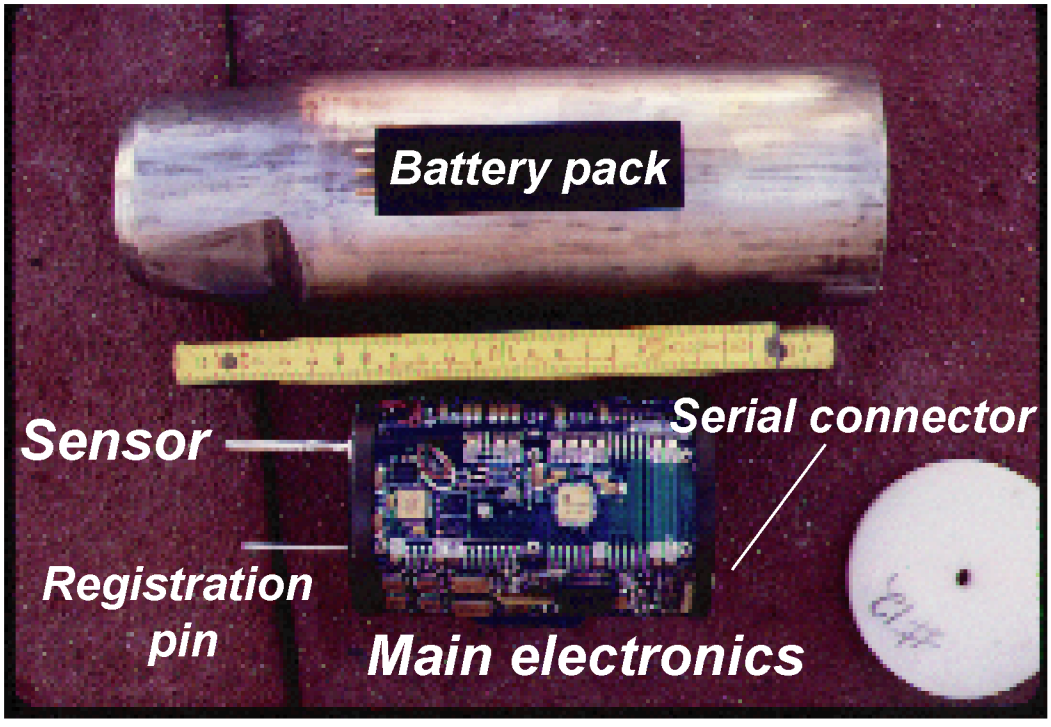
Figure III-1. Examples of (second-generation) APC tool data from ODP Leg 139 in Middle Valley [*Shipboard Scientific Party*, 1992b]. A. Complete deployment in relatively cool sediments. B. Expanded view of record from in sediment, including fit of observations to model. Every third observation is plotted for clarity. Early time data are not used in fit because these data tend to not follow the theoretical decay curve. C. Complete deployment in relatively warm sediments. D. Expanded view of record from in sediment, including fit of observations to model. Every third observation is plotted for clarity. Note how much equilibrium temperatures deviate from final in-situ temperatures, indicating why modeling of tool response is required to estimate equilibrium tempertures.

Figure A3-1. Example calibration data from 2006 experiments with APCT-3 tools. A. Temperatures determined with NIST-traceable reference probe. All measured values are shown with thin line. Filled squares indicate time period during which data were averaged to yield the mean ± standard deviation shown. The reference probe and logging system were shut down for the night after 18:20:00, although the tank was left running to allow work to continue the following day with minimal disruption. B. Resistances recorded simultaneously by the three APCT-3 tools. All data recorded during the period shown are indicated with thin lines. Symbols indicate data used to derive mean resistances for this reference temperature, as shown. See discussion in text concerning selection of data windows.

Figure A3-2. Calibration temperatures and residual errors plotted against tool resistance. In all plots, the left axis shows temperature measured with the reference probe, indicated with open squares and a thin line. The right axis shows residual errors between mean temperatures determined with the reference probe and those determined using factory calibrations (provided by the thermistor manufacturer, filled squares), and temperatures determined following calculation of new Steinhart-Hart coefficients (crosses). In all cases, the new coefficients provide residual errors ≤0.002 C °C. A. Tool 1858002C. B. Tool 1858004C. C. Tool 1858005C.


Serial connector
Main electronics
Sensor
Battery pack

A


Battery pack
Sensor
Serial connector
Registration pin
Main electronics

B

Figure I-1

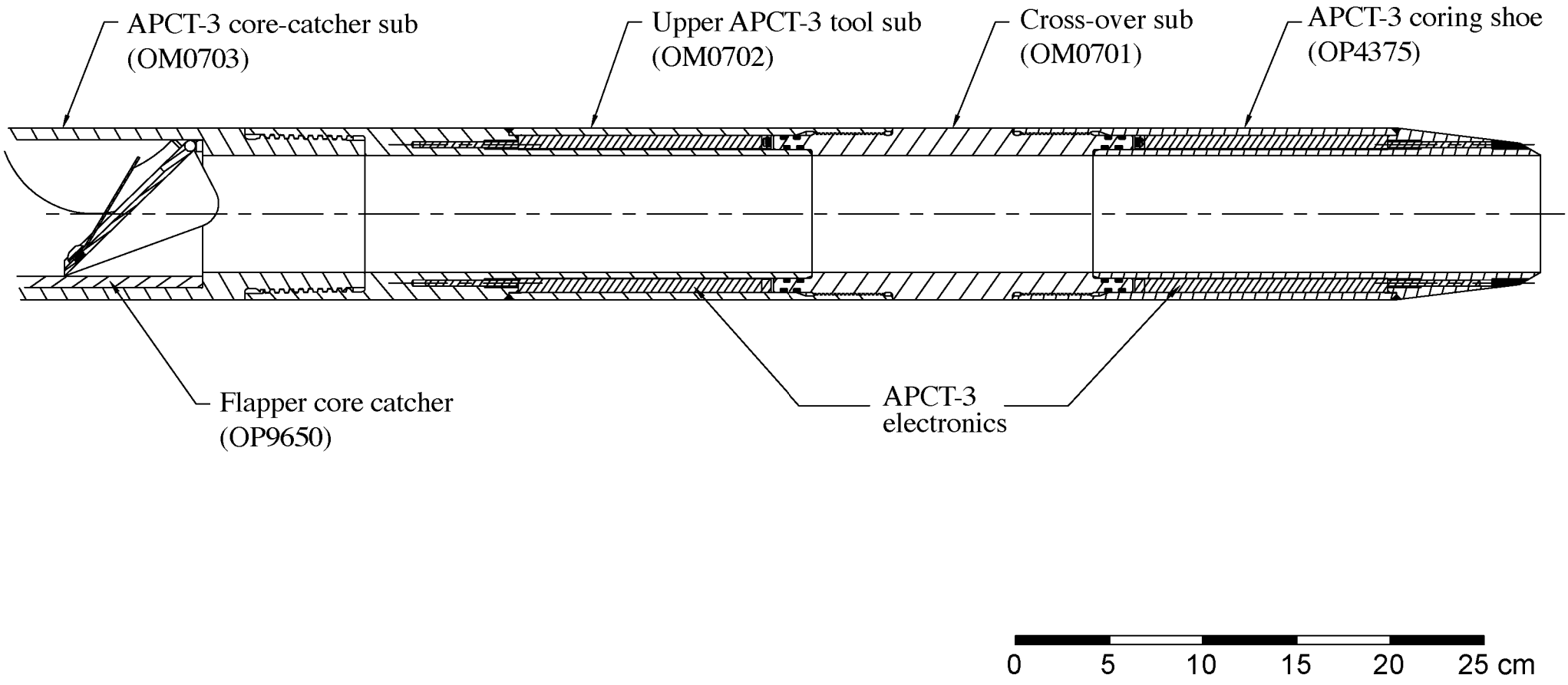

APCT-3 core-catcher sub
(OM0703)
Upper APCT-3 tool sub
(OM0702)
Cross-over sub
(OM0701)
APCT-3 coring shoe
(OP4375)
Flapper core catcher
(OP9650)
APCT-3
electronics
0
5
10
15
20
25 cm

Figure II-1

APCT-3 shoe
Curved
serial
connector
Electronics storage
case
Thermistor probe
Test plug
Batteries
Deck box
APCT-3
tool frame
Top ring
Insertion/extraction tool

Figure II-2

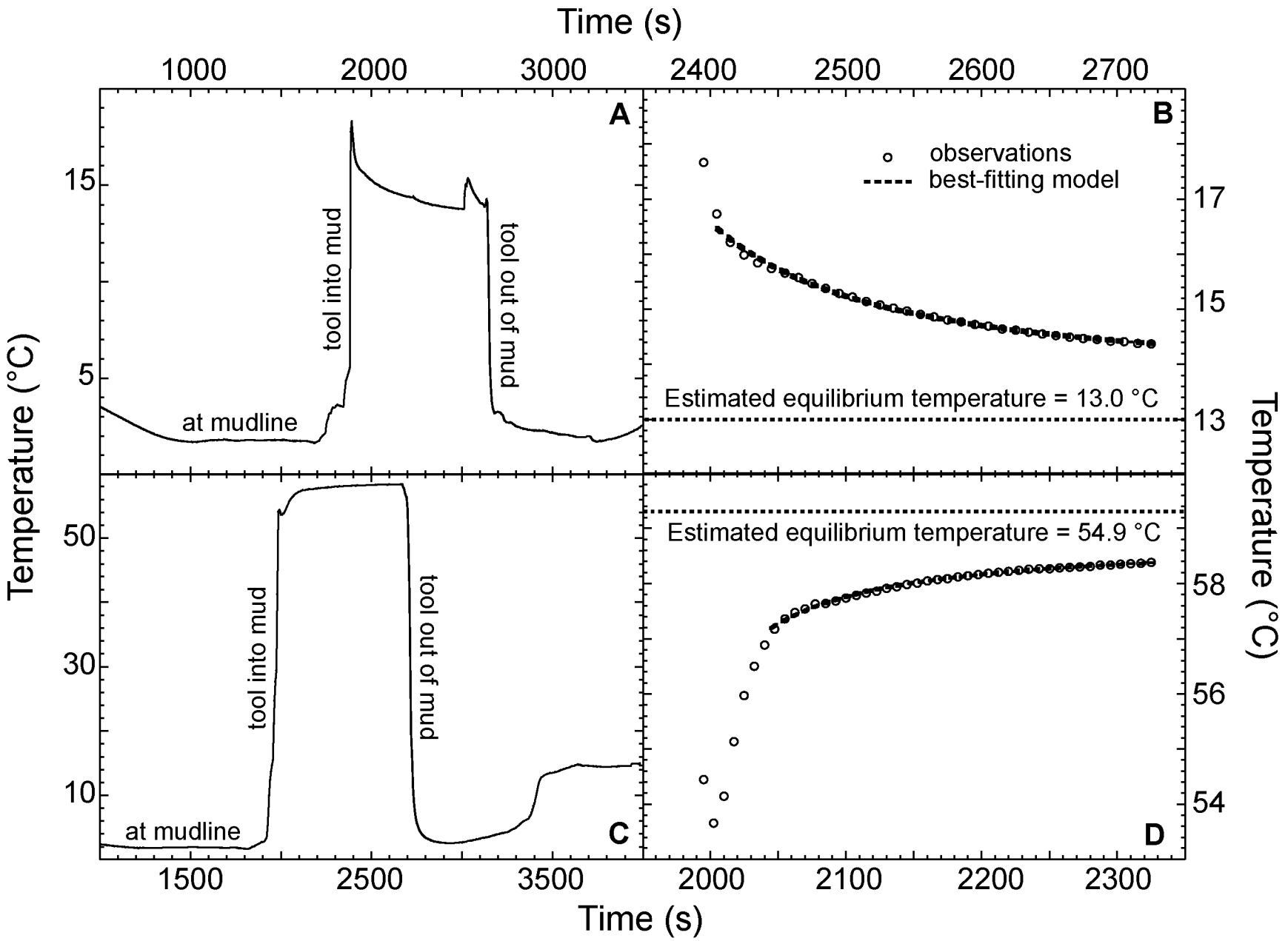
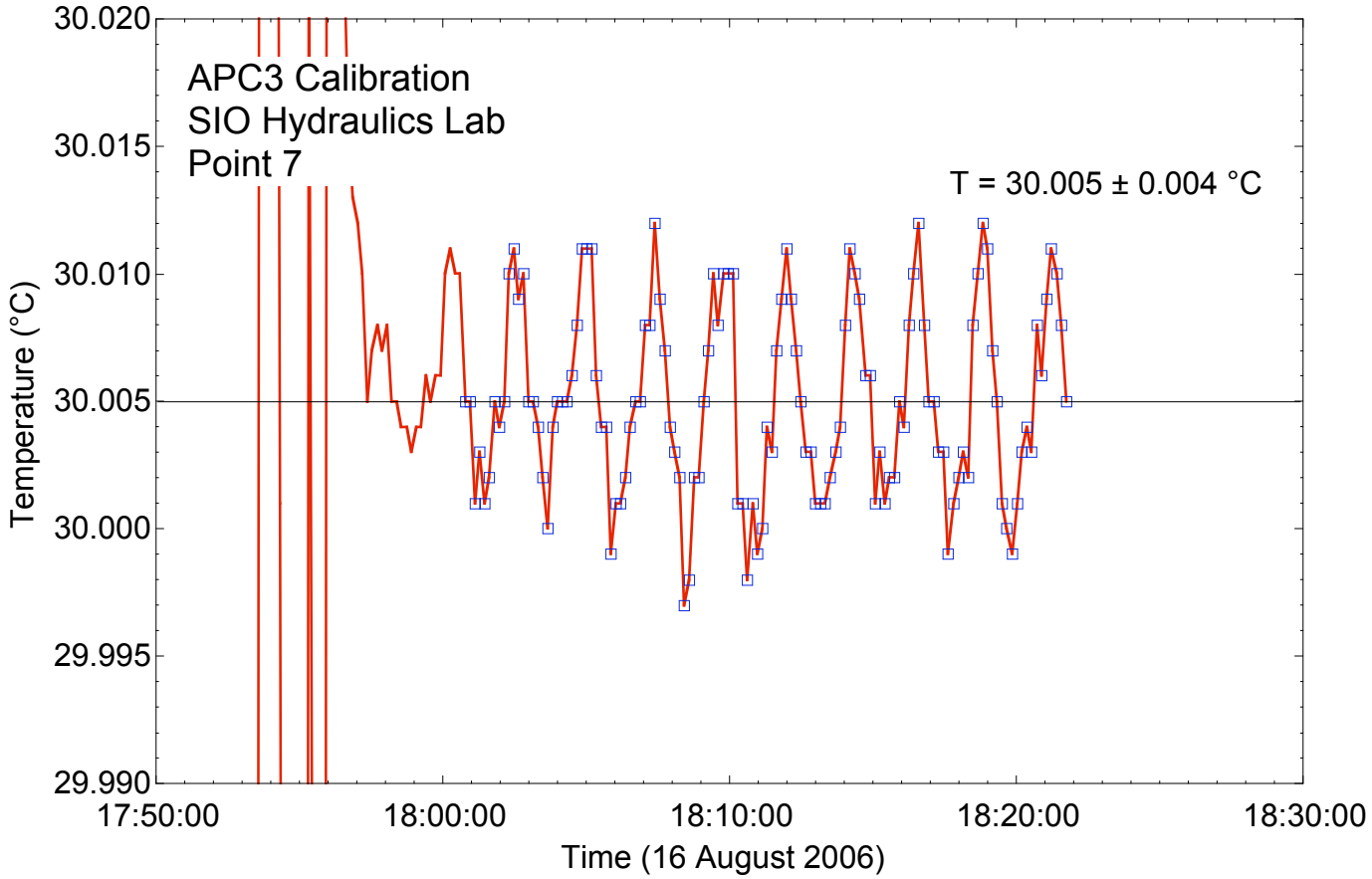

Time (s)
1000
2000
3000
2400
2500
2600
2700
A
B
15
5
tool into mud
tool out of mud
at mudline
observations
best-fitting model
17
15
13
Estimated equilibrium temperature = 13.0 °C
Temperature (°C)
50
30
10
tool into mud
tool out of mud
at mudline
C
Estimated equilibrium temperature = 54.9 °C
58
56
54
D
Temperature (°C)
1500
2500
3500
2000
2100
2200
2300
Time (s)

Figure III-1


APC3 Calibration
SIO Hydraulics Lab
Point 7
T = 30.005 ± 0.004 °C
Temperature (°C)
30.020
30.015
30.010
30.005
30.000
29.995
29.990
17:50:00
18:00:00
18:10:00
18:20:00
18:30:00
Time (16 August 2006)

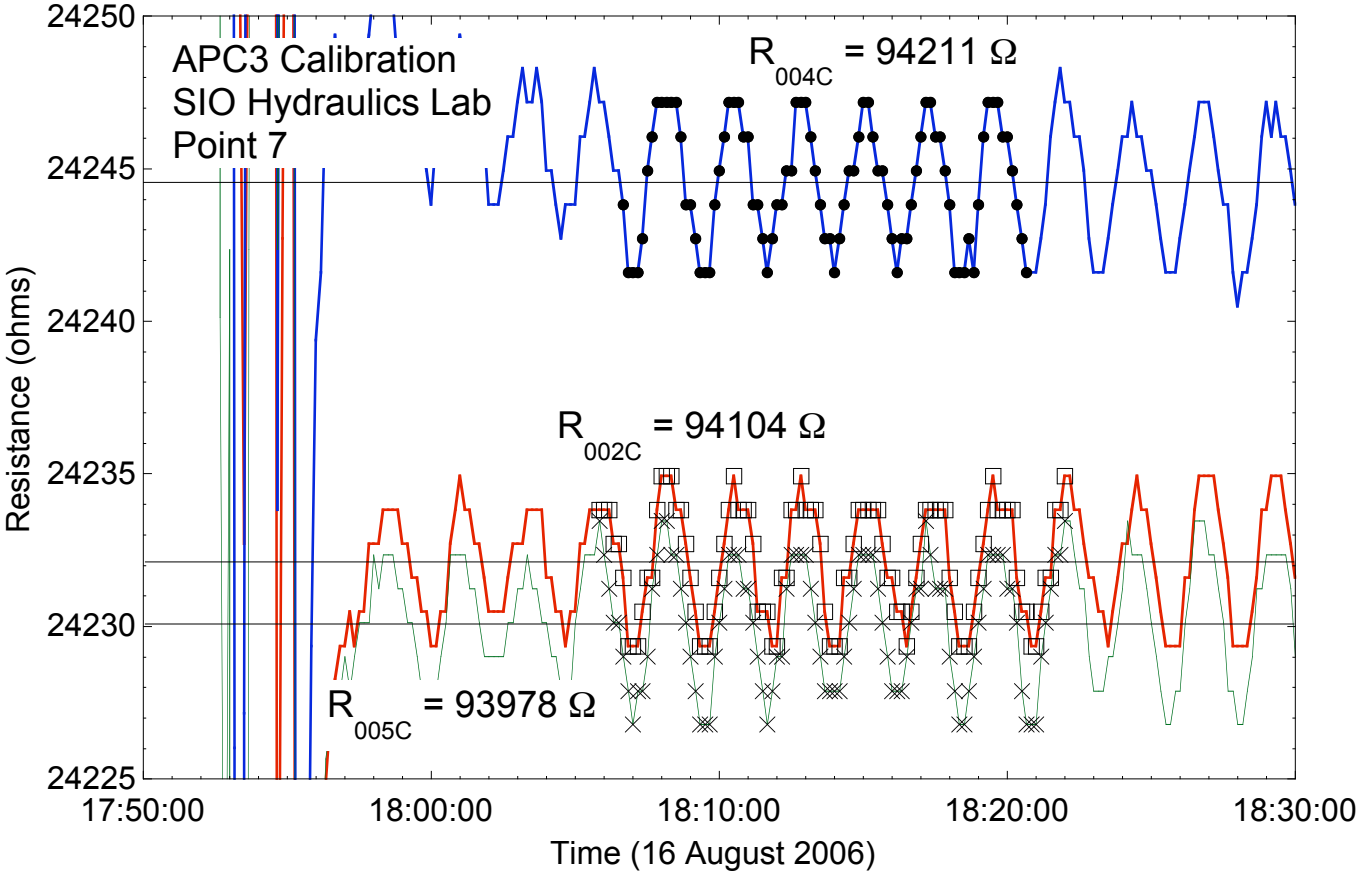

APC3 Calibration
SIO Hydraulics Lab
Point 7
R004C = 94211 Ω
R002C = 94104 Ω
R005C = 93978 Ω
Resistance (ohms)
24250
24245
24240
24235
24230
24225
17:50:00
18:00:00
18:10:00
18:20:00
18:30:00
Time (16 August 2006)

Figure A3-1

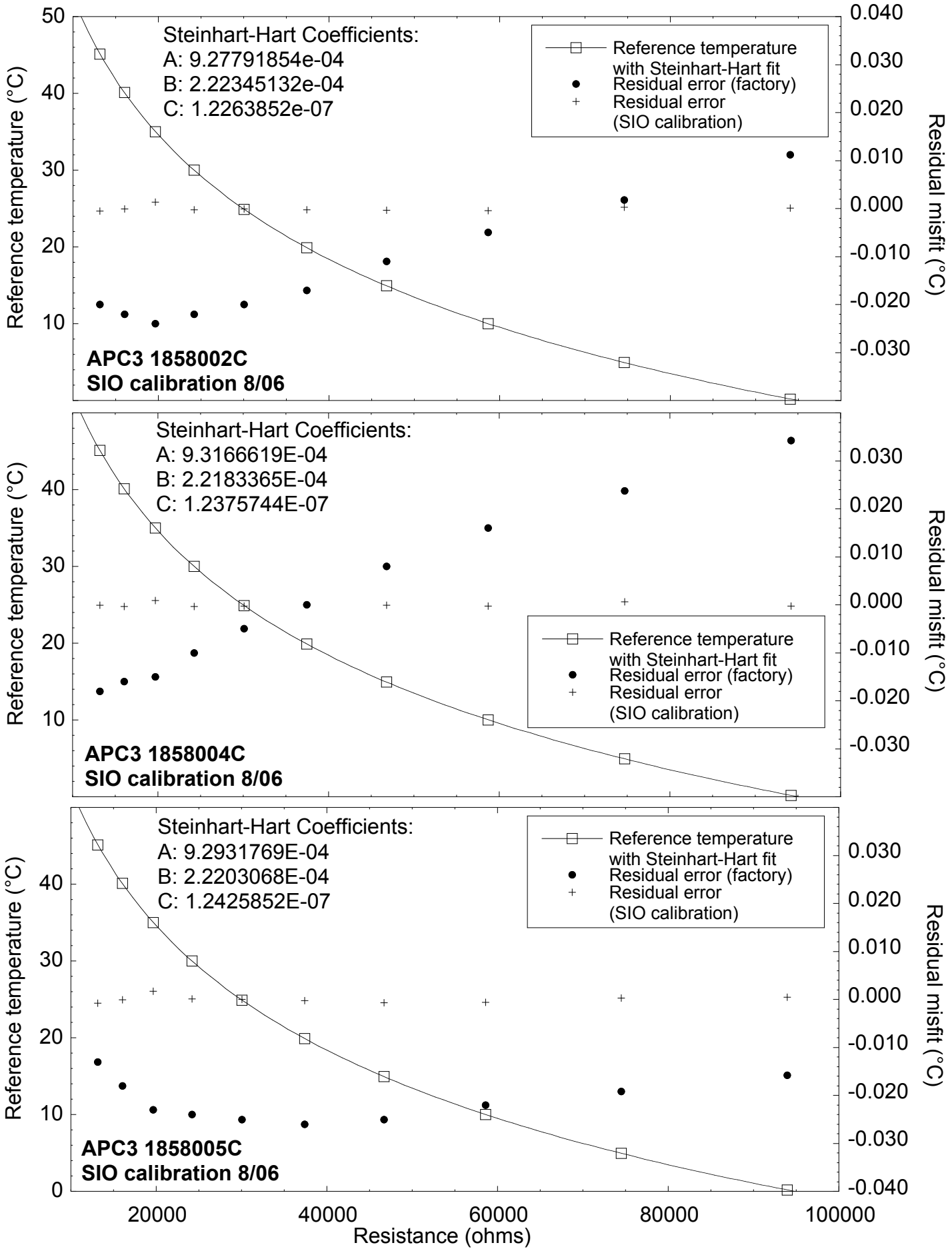

Steinhart-Hart Coefficients:
A: 9.27791854e-04
B: 2.22345132e-04
C: 1.2263852e-07
Reference temperature with Steinhart-Hart fit
Residual error (factory)
Residual error (SIO calibration)
APC3 1858002C
SIO calibration 8/06
Steinhart-Hart Coefficients:
A: 9.3166619E-04
B: 2.2183365E-04
C: 1.2375744E-07
Reference temperature with Steinhart-Hart fit
Residual error (factory)
Residual error (SIO calibration)
APC3 1858004C
SIO calibration 8/06
Steinhart-Hart Coefficients:
A: 9.2931769E-04
B: 2.2203068E-04
C: 1.2425852E-07
Reference temperature with Steinhart-Hart fit
Residual error (factory)
Residual error (SIO calibration)
APC3 1858005C
SIO calibration 8/06
Reference temperature (°C)
Residual misfit (°C)
Resistance (ohms)
0
10
20
30
40
50
20000
40000
60000
80000
100000
0.040
0.030
0.020
0.010
0.000
-0.010
-0.020
-0.030
-0.040

Figure A3-2